

# *Urban water balance and hydrology models*

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## URBAN WATER BALANCE AND HYDROLOGY MODELS

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### INTRODUCTION

The urban water balance ensures conservation of mass of water in the same way the energy balance requires conservation of energy (Chapter 4 for details). By considering all the exchanges in the urban water balance, insight can be gained into the dynamic processes and feedback mechanisms in the urban environment, providing important insights into urban sustainability.

To create a sustainable urban area requires a coherent strategy that applies planning/design tools at the appropriate scale and ensures that actions at one scale are not counteracted at another. These strategies need to apply not only to the built area, but also to the surrounding area that is intertwined. To integrate these sustainability principles into urban planning strategies at the level of land use (1:5000 - 10,000; neighbourhood to settlement) and master plans (1:500 - 1000; building block), knowledge of the urban water balance is needed as a guidance for innovative planning and design on a more detailed level. In addition, an accurate representation of the urban water balance through modelling is imperative for the assessment of future sustainable urban water management practices, realistic simulation of urban surface processes and for predicting the effects of climate change.

In urban areas the water system often consists of two separate parts that strongly interact: the semi-natural surface and groundwater system and the man-made sewer and supply systems. Knowledge of the semi-natural surface and groundwater system is especially important at the level of neighbourhood and master plans, while the man-made sewer and supply systems become essential at the more detailed level.

As this book aims to support planning processes at the scale of city to neighbourhoods and master plans, the emphasis in this chapter is on hydrological models rather than more detailed hydraulic models needed to design an urban sewer system. After a short review of the available types of urban water balance models, two urban water balance models used in the BRIDGE project (Chrysoulakis et al. 2013) SIMGRO and SUEWS are presented. These physically based hydrological models for urban spatial planning are applied in two BRIDGE case study cities, London and Helsinki. The energy and water balances are linked by the evaporative or latent heat flux terms (see Chapter 4 for details). The urban land surface models that determine the surface energy balance fluxes were tested independently, as it has been presented in Chapter 9.

### OVERVIEW OF URBAN WATER BALANCE MODELS

In the literature three general types of urban water balance models exist with varying degrees of complexity and spatial extent. Each is described below.

#### Mass balance models

Models based on the mass balance are largely used to determine the urban water balance for urban hydrology and water management applications. They consider both natural and anthropogenic hydrological systems through the use of a number of empirical relations to determine the fluxes and storage of the urban system for the desired spatial and temporal scale. The latter depends on data availability and resolution (typically daily data are used). These models consider the inputs, outputs, flows and stores of the water balance.

Grimmond & Oke (1986) describe such a model and evaluate it using observations from Vancouver, Canada. That model has been used to study urban irrigation and the urban water link to the energy budget via evapotranspiration. Two urban water balance models developed in Australia for the assessment of water management techniques are Aquacycle (Mitchell et al. 2001) and the Urban Volume and Quality (UVQ) model (Mitchell & Diaper 2005). Aquacycle contains options to apply water management techniques to the urban water balance and was evaluated using data from Woden Valley, Canberra, Australia (Mitchell et al. 2003). UVQ is essentially an expanded version of Aquacycle with the added ability to model contaminant fluxes (Diaper & Mitchell 2007) for a number of cities around the world (Wolf et al. 2007). Site specific input values are required to calibrate and run the models with three nested spatial scales in each (unit block property), cluster (neighbourhood) and the study area as a whole (Wolf et al. 2007). Unlike the Urban Water Balance model of Grimmond & Oke (1986), there is less focus on required meteorological data, with only daily precipitation and potential evapotranspiration values needed.

#### Surface atmosphere transfer schemes

Secondly, urban parameterization schemes used in global and meso-scale numerical weather models are available; examples include the Urban Hydrological Element (UHE) model (Berthier et al. 2004, 2006); the urbanized Submesoscale Soil Model (SM2-U) (Dupont et al. 2006); the combined Town Energy Balance and Interaction Soil-Biosphere-Atmosphere scheme (TEB-806 ISBA) (Lemonsu et al. 2007); and the Surface Urban Energy and Water balance Scheme (SUEWS) (Järvi et al. 2011). Each scheme differs in complexity and focus, but in essence all are formed of a number of surface and subsurface layers and model the surface water balance using inputs from a numerical atmospheric model (typically net radiation and precipitation) and generate outputs for use in the next model time step (evapotranspiration). All the schemes presented use no, or very simple drainage networks and have mixed land uses (urban and natural surface types), each of which have individual surface and hydrologic properties weighted by their relative areal coverage of a particular grid box. Unlike the dedicated urban water balance models, these parameterizations focus only on the external water system.

The UHE model (Berthier et al. 2004, 2006) focuses on simulating storm water runoff and soil infiltration within the urban water balance. Two main layers are used: a surface layer with three possible land cover types (natural, paved and building roof) and a soil layer (subdivided into an upper and lower sub-layer for infiltration purposes), which takes the form of a fine mesh grid. In addition to these layers, there is a storm water drainage system which is represented as a trench collecting all available runoff as well as seepage from soil water (this acts in both directions depending on soil moisture conditions). The original version (Berthier et al. 2004) considered evapotranspiration (and infiltration) by applying a ‘mixed’ boundary condition on modelled soil moisture, observed rainfall and potential evapotranspiration. Further developments included a dual evapotranspiration scheme based on the Penman-Monteith-Rutter-Shuttleworth equation (Grimmond & Oke 1991) for paved and roof surfaces and a scheme based on Feddes et al. (1988) to calculate the potential evaporation and transpiration for the natural surface types (Berthier et al. 2006). Model evaluation was done using site specific parameters and observed meteorological and hydrological variables from the Reze field site, Nantes.

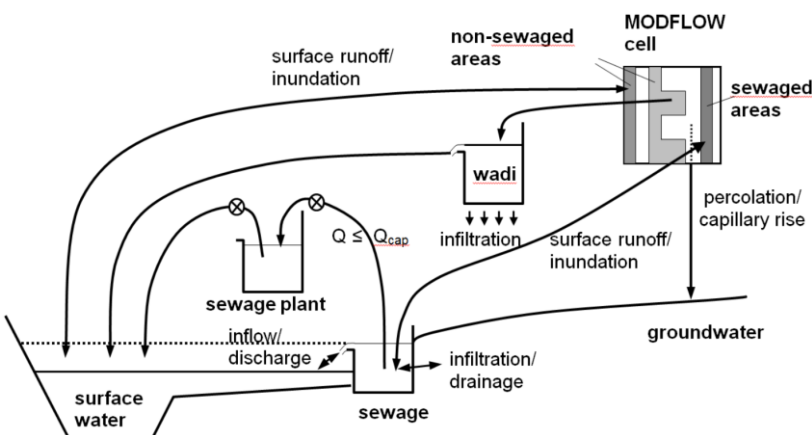
SM2-U is a mesoscale model surface parameterisation scheme (Dupont et al. 2006) formed of four levels (lower atmosphere, surface layer, root zone and deep soil) and a rudimentary drainage network as used in Berthier et al. (2004). It is an extension of Noilhan & Planton’s (1989) ISBA scheme with the addition of four artificial urban surface types (building roofs, paved surfaces, vegetation elements over paved surfaces and paved surfaces below vegetation), each with their own surface properties (Dupont et al. 2006). The scheme was evaluated with data from three measurement sites, two rural and the suburban site at Reze which allowed comparison of the runoff running through the drainage network with the original version of UHE (Berthier et al. 2004). It was concluded that the SM2-U scheme performed well annually and in summer storm events in comparison to UHE but was poor at simulating winter storms as infiltration to and from the drainage network was not modelled.

Lemonsu et al. (2007) also used ISBA but with Masson’s (2000) Town Energy Balance (TEB) urban surface parameterization scheme. The scheme has three layers (the surface and two soil layers) and four surface types, the three ISBA vegetation surfaces (bare soil, soil between vegetation and vegetation) and an urban surface which in TEB is modelled as a three dimensional urban canyon. An off-line simulation of the TEB-ISBA water balance was undertaken using meteorological data to force the model and input parameters from the literature relevant to a suburban area. The results were compared with data from the Reze study area. Discrepancies between modelled and observed runoff suggested further work on the parameterization of surface infiltration through roads was needed (Lemonsu et al. 2007).

The fourth surface parameterization scheme SUEWS simulates the urban water balance components including irrigation, surface runoff, infiltration, evaporation and storage at a local or neighbourhood scale (Järvi et al. 2011). It consists of three layers (the surface and two soil layers) and seven surface types (paved, buildings, evergreen and deciduous trees/shrubs, irrigated and non-irrigated grass and water). SUEWS does not have separate tiles for urban and vegetative surface fractions, but rather dynamic interaction between the different surface types is allowed. The model has been successfully run for Los Angeles, USA, and Vancouver, Canada. As its performance in cold climate cities in wintertime was poor due to the inadequate description of snow, further development has been undertaken (Järvi et al. 2014).

## Hydrological models

Hydrologic models are typically composed of two parts: a surface scheme and a hydrological flow model (described as a natural, anthropogenic or a combination drainage system often represented by a combination of a surface and groundwater module) that moves water through the study catchment. In Figure 10.1 an example of such a model configuration and the processes involved is depicted. Examples of models of this type include: Semi-Urbanised Runoff Flow (SURF) (Rodriguez et al. 2000); the Water and Energy transfer Processes (WEP) model (Jia et al. 2001); the Urban-Runoff Branching Structure Model (URBS-MO) (Rodriguez et al. 2008); the SIMGRO-model (van Walsum & Veldhuizen 2011); and the Urban FOREst Effects-Hydrology (UFORE-Hydro) model (Wang et al. 2008).



**Figure 10.1.** The urban water cycle as represented in the SIMGRO model (van Walsum & Veldhuizen 2011).

These models are typically used to study sewer and drain performance during rainfall events (Rodriguez et al. 2008), assessing impacts of runoff pollution (Rodriguez et al. 2000), simulation of the effects of urban areas on natural catchment flows and flooding (Jia et al. 2001) and the impact of urban trees and canopy interception on runoff and evapotranspiration (Wang et al. 2008, van Walsum & Veldhuizen 2011). The data inputs and parameters required for these models include physical land cover properties (e.g. fraction of impervious land cover and aerodynamic roughness length), surface and subsurface hydrologic

properties (e.g. soil storage capacity), water use information (e.g. mean water use), initial conditions in terms of storage in the study area (e.g. soil moisture) and a range of averaged (period of choice) meteorological data (e.g. net radiation and precipitation).

## APPLICATION OF THE MODELS IN BRIDGE CASE STUDIES

As an illustration of how urban water balance models can be used to consider sustainable planning strategies, the application is presented of two models of the BRIDGE project, i.e. a surface atmosphere transfer scheme (SUEWS) and a hydrological model (SIMGRO). Here SUEWS is applied to Helsinki to evaluate its performance and both models are applied to the London case study. In the next sections a short description of the two sites, model set-up and scenarios is given. A more detailed description of both sites, as well as of the measurements taken at these sites is given in Chapter 5, whereas the urban Planning Alternatives (PA) that considered in BRIDGE are presented in detail in Chapter 3.

## Helsinki

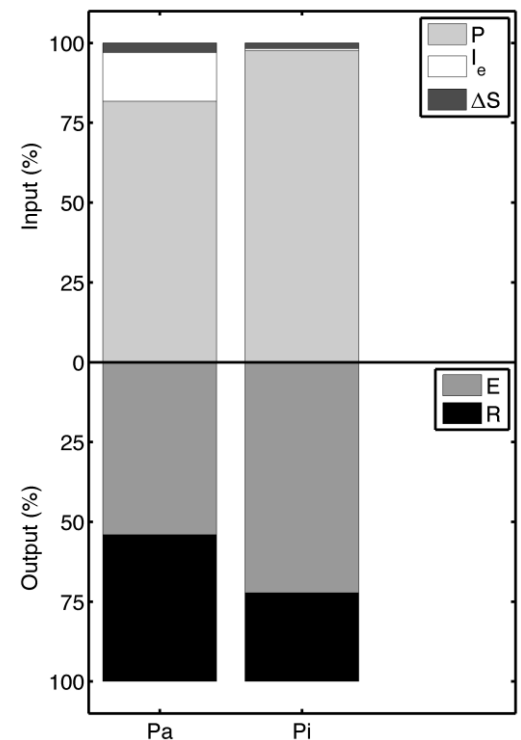
In Helsinki, runoff observations were undertaken in three catchments (see Chapter 5, and Table 10.1): Pasila (Pa) with few pervious surfaces and a complex building and pedestrian road structure, Pihlajamäki (Pi) with much less built-up, or impervious surfaces and Veräjämäki (not included in Table 10.1) where the surface is mainly natural vegetation. The high fraction of impervious surfaces has a clear influence on the water balance. For example, in November 2010 runoff from the high-intensity built catchment was seven times higher than from the low-intensity built catchment. In November 2010, the monthly precipitation 62 mm was observed at the Kumpula site and in the low-intensity catchment 8% of this left the catchment as runoff, whereas in the medium- and high-intensity catchments over 50% of the precipitation ended up in runoff. This shows how increasing impervious surface cover enhances the risk for urban floods, while water storage and evaporation to vegetation cover decreases.

Here SUEWS is used to simulate summer water balance for January - August 2010 at the Pa and Pi catchments (Table 10.1). The first four months is the spin-up time to ensure, such things as soil moisture and surface states are appropriate. The forcing data used were from the nearby SMEAR III measurement station (Järvi et al. 2009). Thus the amount of precipitation at both sites is assumed to be the same (168 mm total for the period), but in Pi the amount of external irrigation is clearly smaller, causing precipitation to be the more important source of water. In Pi there is lots of natural state vegetation whereas in Pa, despite the smaller fraction of vegetation, it is more managed. At both sites, the change in soil water storage helps to maintain evaporation in summer time June to August, i.e. 6 and 3 mm in Pa and Pi, respectively (Figure 10.2). In the highly built-up catchment Pa, clearly less water is evaporated (111 mm  $y^{-1}$ ) than in Pi (125 mm  $y^{-1}$ ), and more water goes directly to runoff. SUEWS has been found to simulate the observed runoff at both catchments well (Järvi et al. 2013) and therefore can be used to examine the effect of different land uses on the water balance components.

	London CAZ	Helsinki Pa	Helsinki Pi
Buildings (-)	0.33	0.20	0.12
Streets (-)	0.34	0.42	0.22
Freshwater (-)	0.06	0	0
Grassland (-)	0.13	0.14	0.26
Coniferous trees/shrubs (-)	0	0	0.10
Broadleaf trees/shrubs (-)	0.14	0.24	0.30
Population density (# $ha^{-1}$ )	96	42	55
Surface area (ha)	2916	23.8	44.8

**Table 10.1.** Existing land-use cover at the Central Activity Zone in London, UK (based on the Mastermap TM, Greater London Authority of 2009) and at the two catchments Pasila (Pa) and Pihlajamäki (Pi) in Helsinki, Finland

**Figure 10.2.** Simulated, using SUEWS, water balance at two catchments Pa and Pi in Helsinki in June –Aug 2010  $P$  = Precipitation,  $I_e$  = irrigation,  $E$  = evaporation,  $\Delta S$  = storage water change and  $R$  = surface runoff.



## London

In London the focus was on the Central Activity Zone (CAZ), as described in Chapter 3. Within this area there are major parks and the river Thames. The River Thames is tidal with an approximately 6 m bi-daily variation in water level in the study area. The elevation of the study area varies between 25 m above sea level in the north to sea level. The CAZ surface is highly sealed, resulting in high rainfall runoff peaks, high temperatures associated with the urban heat island and water scarcity for vegetation if no irrigation is provided. The Greater London Authority has published PA to both cool the city and reduce risk of flooding (Greater London Authority 2010). Increasing the number of trees within the CAZ and increasing areas of green roofs are being considered to mitigate urban warming and peak runoff. The CAZ is targeted and delimited by the London planning strategies for ca 10 years and is the subject of specific planning objectives and goals, which are related to the urban metabolism (see e.g. Greater London Authority 2010, 2011).

For London, the urban PA explored in this chapter with respect to the impact on urban water are:

- PA0: Baseline scenario - The land use map of 2009 (Mastermap TM, Greater London Authority) is used - approximately 70% of the total surface being sealed and approximately 30 % being vegetated areas.
- PA1: Add Street trees: Increase the area covered by street trees to 10% of the total CAZ area (representing a 40% increase of trees). The location of the trees are based on discussions with Greater London Authority (mainly planned around sealed surfaces). The trees are assumed to be all deciduous broadleaved and the soil surface to change from impermeable to highly permeable.
- PA2: Make the roads pervious: We assumed 40% of the roads evenly spread over the model grid become permeable, which is approximately 10% of the total area.

- PA3: Add Green roofs: The location of are based on discussions with Greater London Authority. For a green roof to be added, the roof has to be flat or below 20% and the roof area has to be larger than 25 m<sup>2</sup>. In this scenario, 2% of roofs in the CAZ were changed to green areas.
- PA4: Make roads pervious and add street trees: This alternative combines A1 and A2.
- PA5: Add street trees and increase the surface of green roofs: This alternative combines A1 and A3.

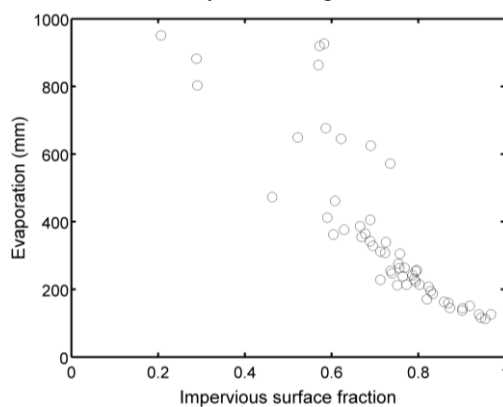
## SIMULATION RESULTS FOR URBAN PLANNING ALTERNATIVES

For London SIMGRO and SUEWS were applied for the year 2010 to a 5.4 km x 5.4 km area at a resolution of 200 m x 200 m and 1000 m x 1000 m, respectively. The study area does not correspond to any water management unit or hydrological sub-catchment, but was chosen to allow the output to be combined with other models that are based on rectangular grids, such as air quality models.

To perform the SIMGRO simulations, current CAZ land cover (see Table 10.1) and the proposed PA 1, 2 and 4 were mapped as 10 Urban Morphological Types (UMTs). Each UMT represents a specific land cover type with specified reservoir characteristics. Not included in the model as presented in this paper are anthropogenic factors, such as watering gardens and leakage of water supply and sewerage pipes. In London leakage of pipes is a significant term in the water balance, i.e. 675 Ml d<sup>-1</sup> leakage in 2010/2011 (Thames Water 2013).

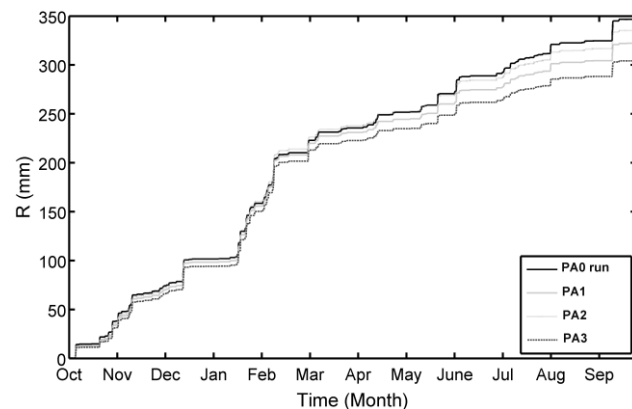
The greener city planning scenarios are compared to a baseline (PA0: CAZ land cover in 2009) with attention to evapotranspiration, soil water shortages, and intensity of runoff peaks.

The SIMGRO results show that if the number of trees or other green areas are increased, the natural soil water storage for the simulated year of 2010 will limit the evapotranspiration rate during a part of the year. If insufficient soil water is available during hot periods, evaporation will be limited and as a result the potential cooling effect by urban green will not be realised. To maintain maximum cooling, either additional irrigation water, or a greater soil water storage capacity to retain precipitation is needed. Figure 10.3 shows the relation between the fraction of impervious surface and the water limited evaporation rate for the different grid cells in the study area using the SUEWS model.



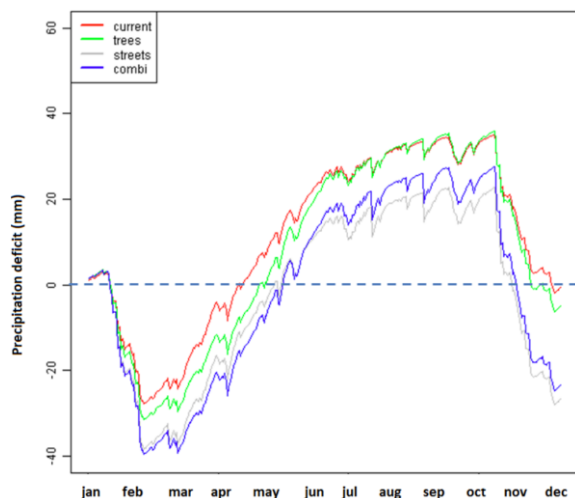
**Figure 10.3.** The relation between the fraction of impervious surface and annual evaporation rates simulated using SUEWS for individual grid cells (1 km x 1 km) of the CAZ, London UK.

**Figure 10.4.** Cumulative hourly runoff for a highly built-up grid cell (1 km x 1 km) in central London with the different PA, using the SUEWS model: Base line = control (PA0), Alt1 = 40% increase of trees (PA1), Alt2 = 2% of roofs greened (PA3) and Alt3 = combined trees and green roofs (PA3).



The SUEWS simulations predict that covering an additional 10% of the total area with street trees (PA1) will reduce runoff by 7%. In contrast, if 2% of the total area is transformed to areas with green roofs (PA3), the reduction is 3% (Figure 10.4). However, if, they are combined (PA5) there is a greater reduction in surface runoff (12 %) as more water is horizontally redistributed and subsequently consumed by evaporation. SIMGRO simulates very similar reductions in runoff (7%) for the PA with additional street trees (PA1), while the increase in permeable streets (PA2) caused a decrease of 14% in runoff, with the combination of both measures (PA4) resulting in a decrease of 17% compared to the total runoff of the baseline situation (PA0).

That effects of such measures are dependent on time of year and influence one another. This is confirmed by the SIMGRO calculated excess precipitation (Figure 10.5) which indicates when additional water would be needed to sustain maximum (energy limited) evapotranspiration. In the summer months, water shortages resulting from the combined alternative (PA4) becomes larger than the permeable street (PA2) alternative. As noted above, the addition of trees in both PA1 and PA4 requires additional water to maximise evapotranspiration.

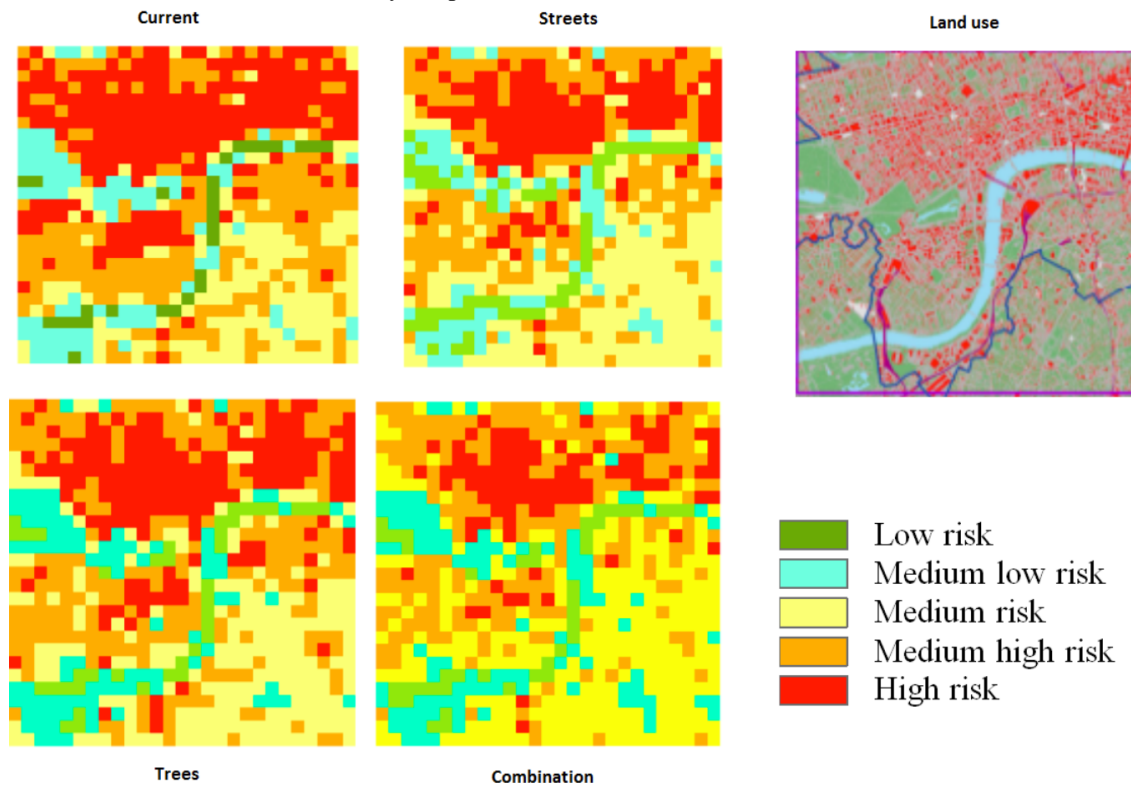


**Figure 10.5.** Annual cumulative precipitation shortage (negative numbers indicate precipitation excess) in 2010 for the control and the three PA, using the SIMGRO model for the CAZ area in London UK: current = 70% sealed and 30 % of area green (PA0), trees = 40% increase of trees (PA1), streets = 40% more permeable streets (PA2) and combi = combined (PA4).

To support decision making in planning processes, spatial representation of areas at risk, or not complying to a certain threshold value either represented by a physical variable, or an index, are desirable. Figure 10.6 presents as an example, the areas at risk for reduced evapotranspiration rates in summer. These areas are expected to be associated with warmer temperatures because of reduced cooling. For the combined alternative (PA4) there is a decrease of 25% in risk of warmer temperatures because of lack of cooling compared to the baseline (PA0); for



infiltrating streets (PA2) a decrease of 20%, and for trees (PA1) 15%. The areas of medium risk increase for every alternative; for the combination (PA4) with 15%, for streets (PA2) 10%, and for trees (PA1) 5%. These changes in risk levels can be directly related to the land cover changes of the alternatives. These simulations show (see Figure 10.6) that increase of urban green space in combination with water availability (necessary to support the evaporation rates) does increase actual evapotranspiration which contributes to a decrease of city temperatures.



**Figure 10.6.** Spatial differences in risks for higher temperatures in 2010 because of low evaporation rates for the control and the three PA, using the SIMGRO model for the CAZ area in London UK: Current = 70% sealed and 30 % of area green (PA0), Trees = 40% increase of trees (PA1), Streets = 40% more permeable streets (PA2) and combi = combined (PA4). The panel on the right depicts the current main land cover use types: red = built up, green = vegetated area, light blue = open water bodies (e.g. river, lakes, ponds).

## DISCUSSION and CONCLUSIONS

Risk maps give a quick overview of the effects of the implementation of urban PA and can be useful for an evaluation and understanding the consequences. In this study, alternative strategies for a greener city, the CAZ of London, UK, were compared with a baseline and evaluated focussing on the effects of an increase of actual evapotranspiration and a decrease of intensity in rainfall generated runoff peaks. The risk maps (see Figure 10.6) showed that additional urban green space is most effective in dominantly sealed areas.

If the goal is to use evaporation increases to lower air temperature for human comfort, not only the evaporation rate but also the meteorological conditions will be important (e.g. Müller et al. 2013). Obviously, the greatest opportunity for change is in the areas with a large fraction of sealed surfaces. However, to make such a shift possible in these areas will mean a drastic land use change from built-up to vegetated surfaces, or open water. To implement such alternatives sufficient water needs to be available at the appropriate time. This may require irrigation.

Not surprisingly, the quality of the results are highly dependent on the quality of the input data (forcing data, model parameters) and models used. It is essential that the models are extensively evaluated to ensure that they are capable of performing appropriately for both current conditions and proposed PA. Thus the measurements of evaporation (see Chapter 5 for details) and evaluation of these processes (e.g. Chapter 9), are critical to not only energy, but also to water exchange related processes. Models, such as presented in this chapter, allow for a rapid assessment of different PA, while simultaneously providing insights in the dynamic processes and interactions between different components of the hydrological cycle in the urban environment. As such these models can aid in the identification of potential problem areas associated with different urban PA and support planning processes at the relatively large scale of settlements and master plans.

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